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Correlation between energetic ion enhancements and heliospheric current sheet crossings in the outer heliosphere

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[1] Voyagers 1 and 2 observed highly-variable beams of energetic ions in the foreshock region upstream of the termination shock (TS). At Voyager 2 (V2), the ion intensities are generally not related to the plasma properties. At Voyager 1 (V1), the beams are often coincident with crossings of the heliospheric current sheet (HCS). The V1 intensity peaks occur when the HCS is crossed from negative to positive magnetic polarities and V1 is within a few AU of the TS. Two mechanisms are considered: current sheet drift and streaming of ions from the TS along magnetic field lines which are parallel to the HCS. The current sheet drift hypothesis predicts that enhancements observed at V2 will occur when the HCS is crossed in the opposite direction, from positive to negative magnetic polarity, since V2 is at southern heliolatitudes.

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1. Introduction

[2] Voyager 1 (V1) observed two periods of enhanced energetic particle fluxes before it crossed the termination shock (TS) in December 2004 [*McDonald et al.*, 2003; *Decker et al.*, 2005; *Stone et al.*, 2005]. The first TS particle event (TSP1) began in mid-2002 and persisted until early 2003. The second event (TSP2) began in early 2004 and persisted until November 2004. These events were characterized by increased fluxes of ions in the keV to MeV energy range which were highly anisotropic, flowing along the magnetic field in the direction outward from the sun. The fluxes of these ions were highly variable; *Richardson et al.* [2005] showed that periodicities were present at about 16 and 26 days (1 solar rotation = 25.4 days). The peak intensities of these ions are comparable to the intensities observed in the heliosheath.

[3] Since the plasma experiment on V1 is not working, the relation between the V1 TS events and solar wind plasma is not known. Propagation of Voyager 2 (V2) data to the location of V1 suggested that large pressure changes in merged interaction regions (MIRs) produced changes in the particle intensities [*Richardson et al.*, 2005]. V2 observed its first TSP event starting in 2005 [*Decker et al.*, 2006]; we discuss the correlation between plasma parameters and particle intensities for that event.

[4] This paper shows that peaks in the V1 energetic ion intensities often coincide with crossings of the HCS. These flux enhancements only occur when the HCS crossing is in the direction from negative to positive magnetic polarity. We discuss two hypotheses to explain these observations; that these enhancements result from current sheet drift or from direct streaming of the ions along the HCS from the TS.

2. Observations

[5] Figure 1a shows 6-hour averages of the 2–3 MeV H intensities measured by the V1 Cosmic Ray Subsystem (CRS) Low Energy Telescope D from year 2004.1–2004.9 as V1 moved from 91 to 94 AU. Figure 1b shows 1-hour averages of the azimuthal angle of the magnetic field measured by the V1 magnetometer experiment, where 90° is along the Parker spiral in the direction connecting to the northern hemisphere (negative polarity) of the Sun and 270° connects to the southern hemisphere (positive polarity). For the present solar cycle with $qA < 0$, the magnetic field in the northern hemisphere has a negative magnetic polarity with field lines spiraling towards the sun and the magnetic field in the southern hemisphere points in the opposite direction. Figure 1c shows the elevation angle of the magnetic field where 90° is northward.

[6] We identified 13 peaks in the 2–3 MeV H data with intensities over 0.5 in TSP2 and placed dashed lines at the locations of those peaks. These peaks are numbered at the top of Figure 1. For at least 8 of these 13 events (1, 4, 7, 8, 9, 11, 12, 13), the intensity peak coincides with a crossing of the HCS. For all 8 of these events, the direction of the HCS crossing is from negative to positive polarity. For one event (6), the peak is not near a HCS crossing and for 4 events (2, 3, 5, 10) the HCS crossing is not clean and the crossing time is ambiguous. Near case 6, the magnetic field was radial for many days so the peak may result from a connection of the field lines to the TS. While not all crossings of the HCS from negative to positive polarity coincide with intensity peaks, no crossing from positive to negative polarity coincides with an intensity peak.

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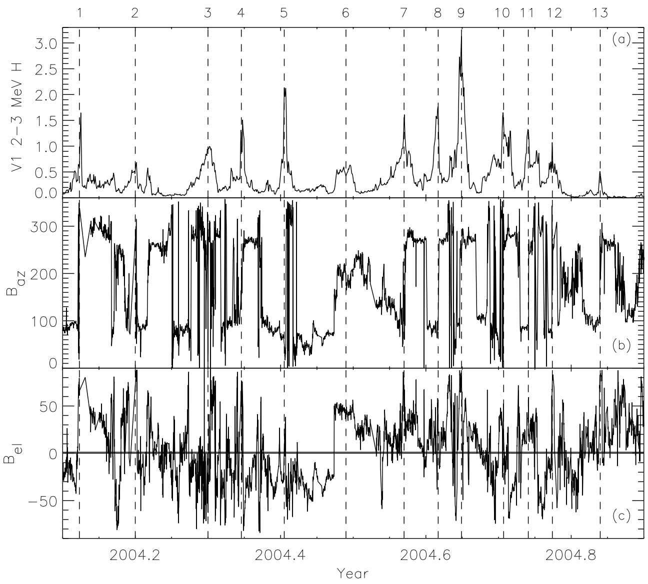

Figure 1. (a) V1 CRS 6-hour averages of the 2–3 MeV H intensities ($cm^{-2}s^{-1}sr^{-1}MeV^{-1}$) during TSP2, (b) the azimuthal angle of the magnetic field, and (c) the elevation angle of the magnetic field. Dashed lines are drawn through peaks in the CRS intensities.

[7] We also looked at peaks in TSP1: those peaks are not correlated with HCS crossings. The intensity peaks are smaller and wider, which suggests that V1 was farther from the shock.

3. Mechanisms

[8] We consider mechanisms which could produce these signatures. The foreshock particles stream along magnetic field lines from the TS. Changes in the connection location on the shock or in the connection distance could change the particle intensities. But the connection would have to change systematically at only negative to positive polarity HCS crossings. We list the observations here:

[9] 1) The TSP particles stream along the magnetic field lines.

[10] 2) Peaks in TSP2 2–3 MeV H intensities occur near negative to positive HCS crossings.

[11] 3) The TSP2 peak intensities at these HCS crossings are comparable to the intensities in the heliosheath.

[12] 4) The magnetic field often has a large northward component at the HCS crossings.

[13] 5) TSP1 data do not show a relationship between particle intensity and HCS crossings.

[14] We consider two mechanisms which could explain these observations, current sheet drift perpendicular to the magnetic field along the HCS and streaming of ions along magnetic field lines which turn parallel to the HCS.

[15] The association of intensity peaks only for negative to positive HCS crossings suggests that current sheet drift [*Burger and Potgieter*, 1989] could be important. Figure 2 shows a schematic diagram of this hypothesized scenario with the HCS tilted 45° and a constant solar wind speed. As the Sun rotates, the V1 and V2 spacecraft, which are at 34°N and 26°S heliolatitude, respectively, are crossed by the outward moving HCS and move between negative and positive polarity magnetic sectors. Figure 2 is highly idealized and the real picture is much more complex. In the outer heliosphere a recurrent sector pattern is not observed, but individual sectors with a wide range of sizes are often present [*Burlaga et al.*, 2003].

[16] The TS in Figure 2 is at 94 AU at the nose and is blunt (i.e., has a larger radius of curvature than a circle of radius 94 AU); we use a rough approximation of the shape of the TS given by *Opher et al.* [2006] and include their North-South asymmetry. When V1 is within 1–2 AU of the TS and the HCS passes the spacecraft from negative to positive polarity, the HCS connects V1 to a lower-latitude part of the TS.

[17] If a particle trajectory were within 2 gyroradii of the HCS, where the magnetic field direction reverses, the particle would experience a fast current sheet drift. The extreme case is when the particle guiding center is on the HCS and the particle follows an "S"-shaped orbit, moving perpendicular to the magnetic field in the plane of the HCS. The particle drift speed depends on the distance of its guiding center to the HCS. On average, particles drift at 1/6 of their speed [*Burger and Potgieter*, 1989]. For the current solar magnetic polarity qA < 0, ions drift inward along the HCS and electrons drift outward. Current sheet drift would bring particles to V1 upstream from the TS and from lower latitudes. For a 2.5 MeV proton, the average drift speed is 2.5 AU/day and its gyroradius in a 0.05 nT magnetic field is 0.031 AU. This yields a HCS thickness of 0.124 AU for 2.5 MeV protons. For the observed average V2 solar wind speed of 380 km/s, these structures of enhanced proton flux would pass V1 in 0.54 day. However, the enhancements seen by V1 are often wider than 0.54 day. Particles may have spread through cross-field diffusion. Another possibility for the wider particle enhancements is

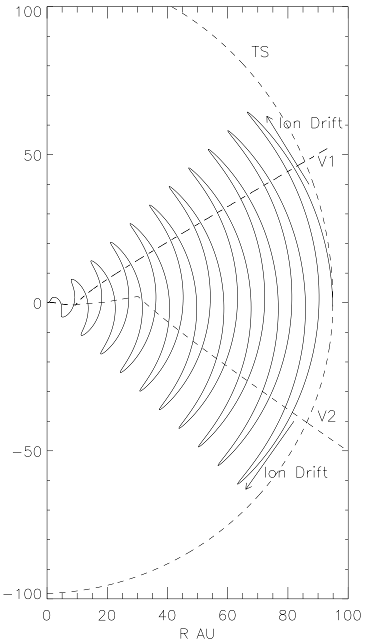

Figure 2. Schematic diagram of the HCS inside the TS. The TS is shown by the dashed curve and the Voyager 1 and 2 trajectories by the dashed lines.

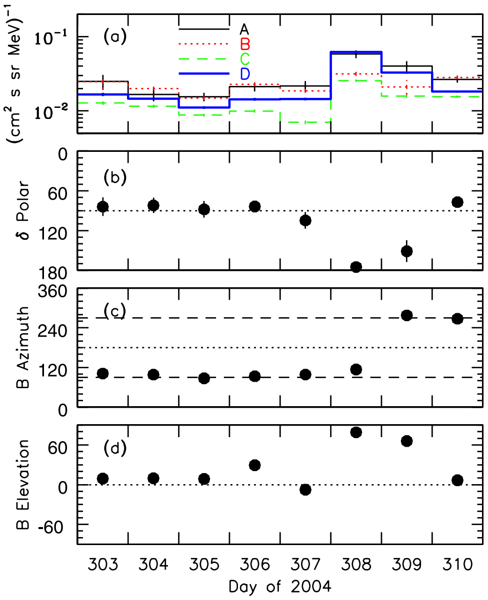

Figure 3. (a) Daily-averaged intensities of 3.3–7.8 MeV protons at V1 in the four LET telescopes (labeled A, B, C, and D) versus time. The view directions of the telescopes can be found in work by *Cummings and Stone* [2005]. (b) Polar angle of the particle flow direction in the RTN coordinate system based on a first-order anisotropy analysis. The points plotted represent the directions from which the particles are coming. (c) Azimuth angle of the magnetic field vector. (d) Elevation angle of the magnetic field vector.

that V1 may skim along the HCS, although the elevation angle of the HCS is usually large at large radial distances from the sun.

[18] This scenario seems qualitatively feasible, but quantitative understanding is more complicated. The HCS structure and the particle drifts which result are complex. Current sheet drift would be superposed on the streaming of the particles along the magnetic field lines. These particles probably stream along the field from the TS; comparison to the *Opher et al.* [2006] results shows that the connection length is of order 20–30 AU. If this estimate were correct and the drift speed is 1/6 of the particle speed, current sheet drift would result in a 5 AU movement of particles inward along the HCS. Since the HCS is highly tilted, most of this motion would be to higher latitudes.

[19] The direction of the current sheet drift is shown in Figure 2. Ions from the TS can drift along the HCS to V1 when the HCS crossing is from negative to positive polarity. The enhancements are not observed at positive to negative polarity HCS crossings; the ions would have to drift to high latitudes and back to V1, a distance of 40 AU, to be observed. Note that for V2 the geometry is reversed; particles would drift along a short path to V2 for positive to negative HCS crossings.

[20] If these ions reach V1 via current sheet drift and their intensity peaks sharply at the HCS, we would expect to see a gradient anisotropy in the same direction as the drift flow, which is roughly in the +N direction. (We use the RTN coordinate system, where R is radially outward, T is in the solar equatorial plane and positive in the direction of the solar rotation, and N completes the right-handed system). The magnitude of the anisotropy is equal to the ion gyroradius divided by the scale size of the particle density gradient [*Jokipii and Kopriva*, 1979]. If the particle pitch-angle distribution is not symmetric, we will see additional anisotropy along the magnetic field. The magnitude of the field-aligned anisotropy mainly depends on the particle pitch-angle distribution function.

[21] The anisotropies can be estimated from the particle intensity data in the top panel of Figure 1. The anisotropy δ is

$$\delta = \mathrm{r}_g/\mathrm{L}$$

where L is the scale of the gradient G given by

$$\mathrm{L} = 1/\mathrm{G}$$

Note that this L is different than the half width L_{hw}, given by

$$L_{hw} = -(\ln 0.5)/\mathrm{G}$$

then

$$L_{hw} = -(\ln 0.5)\mathrm{L}$$

So

$$\delta = \mathrm{r}_g/\mathrm{L} = -(\ln 0.5)\mathrm{r}_g/L_{hw} = 0.69\ \mathrm{r}_g/L_{hw}.$$

[22] Since L_{hw} = 0.25 AU from inspection of the peaks in 2–3 MeV H in Figure 1 and r_g for 2.5 MeV H is 0.03 AU, then

$$\delta = 0.08$$

An anisotropy δ this small would not be detected by the Voyager instruments.

[23] Figure 1 shows that the magnetic field is often northward near the HCS crossings. This change in field direction not only complicates the drift pattern but also raises the possibility that the new field direction gives a better connection to the shock. Figure 1 shows that most of the "good" events have a northward turning of the field at or near the HCS and particle enhancement. Of the eight events, 1, 4, 7, 9, 12, and 13 have magnetic field elevation angles >70° and 8 and 11 have angles above 50°.

[24] We do not understand the origin of these northward magnetic fields, but they could provide a shorter connection to the TS than the azimuthal fields. The TS may be asymmetric, closer to the Sun in the south than the north [*Opher et al.*, 2006]. Depending on the distortion, the distance to the TS southward may be smaller than that in the azimuthal direction, so the particles could reach V1 with less scattering loss. Other possibilities are that the HCS provides a conduit for the particles where losses are less than along the azimuthal field and/or the particle source is large where the HCS intersects the TS.

[25] Figure 3 shows an example of this northward turning of the magnetic field and particle streaming for event 13. The top panel shows the particle intensities, the second

panel the polar angle of the flow, the third panel the azimuthal angle of the magnetic field and the fourth panel the elevation angle of the field. Just before the HCS the field turns northward with elevation angles near 90°; the direction of particle streaming also turns so that ions head northward. The time period of the northward flow and ion intensity enhancement coincide, which suggests the northward turning of the field led to better connection to the TS.

[26] This streaming source should not depend on the direction of the HCS crossing since particles can stream along the field in either direction (whereas they can drift only one direction). Thus the lack of intensity peaks for positive to negative HCS crossings is a challenge for this hypothesis. Figure 1 shows that the magnetic field often has a strong northward component at the intensity peaks; this northward turning of the field occurs more often at negative to positive polarity HCS crossings than the reverse and could result in intensity increases being observed in only one crossing direction. But the magnetic field is northward at the negative to positive polarity HCS crossings at 2004.16, 2004.73 and perhaps at 2004.63 and ion intensities are not enhanced. We note that the magnetic field sometimes turns northward (Figure 1) at times not associated with HCS crossings; these times do not have enhanced particle intensities even though the connection to the TS should be the same as for northward field in the HCS. Perhaps solar wind structures other than the HCS have scales too small to provide a good connection to the TS.

4. Discussion and Summary

[27] Intensity increases of the energetic ions observed in the foreshock region upstream of the TS by V1 are often associated with crossings of the HCS. The magnitudes of the peak intensities are similar to the intensities observed in the heliosheath, so the connection to the TS must be good. These increases are only observed when the HCS crossings are from the negative to positive polarity of the magnetic field and only when V1 is within a few AU of the TS. These increased intensities may result from ions drifting inward along the HCS. The geometry of the HCS intersection with the TS is consistent with this interpretation. But the HCS structure is complex and more detailed modeling of the particle drifts is needed.

[28] Another possibility is that the observed northward turning of the magnetic field at these HCS crossings provides better connection to the TS. This hypothesis is supported by the observed northward streaming of particles along the field since distances to the TS are shorter at southern latitudes [*Opher et al.*, 2006]. The reason for the enhanced northward field at negative to positive polarity HCS crossings is not known and one would expect this mechanism to produce enhancements for both directions of HCS crossings when the magnetic field elevation angle is large, which is not observed.

[29] For either mechanism, the connection of V1 to the TS along the HCS allows us to probe TS ion populations at other heliolatitudes than those of the Voyagers and may suggest that particle intensities are higher at lower latitudes at the TS.

[30] We consider other possibilities. The intersection of the HCS and the TS could be a preferred region for accelerating particles. In this case the enhanced fluxes at the HCS would correspond to the enhanced source. Another possibility is that transport is more efficient, with less scattering, along the HCS, giving enhanced fluxes near the HCS. For both these hypotheses, we would need to explain why the enhancements are observed for HCS crossings in only one direction. Perhaps the northward magnetic field combined with another mechanism could create this asymmetry. But this observation is difficult to explain without invoking current sheet drift.

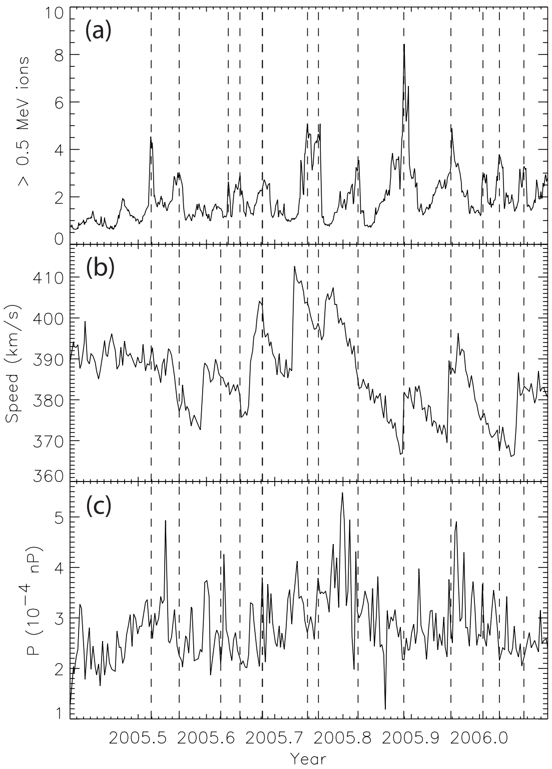

Figure 4. V2: (a) the counting rate of >0.5 MeV ions, (b) the solar wind speed, and (c) the solar wind dynamic pressure.

[31] V2 has observed ion intensity increases similar to those observed by V1 since mid-2005. Those intensities also have a quasi-periodic structure. A Lomb-Scargill periodogram of the V2 CRS >0.5 MeV ion count rates shows a peak power at just over 25 days, or 1 solar rotation. Figure 4 compares the V2 CRS >0.5 MeV ion counting rate to the plasma speed and pressure. We pick out 13 intensity peaks, comparable to the number observed in the second V1 foreshock encounter. Peaks 9 and 10 are associated with shocks and these intensity increases are likely due at least partially to shock acceleration. For the other particle peaks, the plasma speed, density, and pressure do not seem to be correlated with the particle intensities. We conclude that the plasma parameters are only occasionally associated with peaks in the particle intensities but, extrapolating from the V1 results, these peaks may be associated with HCS crossings. When magnetic field data become available from mid-2005 onward for V2, the current sheet drift hypothesis predicts that the peaks in the particle intensity will lie near the HCS crossings. Since V2 is south of the helioequator,

these increases would be observed only at positive to negative polarity crossings of the HCS.

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